# On the Baseline Flux Determination of Microlensing Events Detectable with the Difference Image Analysis Method

Cheongho Han

Department of Astronomy & Space Science,
Chungbuk National University, Chongju, Korea 361-763
cheongho@astronomy.chungbuk.ac.kr

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## ABSTRACT

To improve photometric precision by removing blending effect, a newly developed technique of difference image analysis (DIA) is adopted by several gravitational microlensing experiment groups. However, the principal problem of the DIA method is that, by its nature, it has difficulties in measuring the baseline flux $F_0$ of a source star, causing degeneracy problem in determining the lensing parameters of an event. Therefore, it is often believed that the DIA method is not as powerful as the classical method based on the PSF photometry in determining the Einstein time scales $t_E$ of events.

In this paper, we demonstrate that the degeneracy problem in microlensing events detectable from the searches by using the DIA method will not be as serious as it is often worried about. This is because a substantial fraction of events will be high amplification events for which the deviations of the amplification curves constructed with the wrong baseline fluxes from their corresponding best-fit standard amplification curves will be considerable even for a small amount of the fractional baseline flux deviation $\Delta F_0/F_0$. With a model luminosity function of source stars and under realistic observational conditions, we find that $\sim 30\%$ of detectable Galactic bulge events are expected to have high amplifications and their baseline fluxes can be determined with uncertainties $\Delta F_0/F_0 \leq 0.5$.

*Subject headings:* gravitational lensing – dark matter – photometry – stars: luminosity function

## 1. Introduction

Detection of a large number of events is one of the big challenges in microlensing searches. Classical solution to this challenge is observing fields with greatest density of stars such as the Galactic bulge (Alcock et al. 1997a; Udalski et al. 1997; Alard & Guibert 1997) and the Magellanic Clouds (Alcock et al. 1997b, 1997c; Ansari et al. 1996). While the use of such crowded fields increases the event rate, it also limits the precision of the photometry due to blending (Di Stefano & Esin 1995; Woźniak & Paczyński 1997; Han 1997; Alard 1997). In addition, with the use of the classical method based on PSF photometry one can monitor only stars with resolved images, and thus the number of source stars is limited by crowding.

These problems of the classical method of microlensing experiments can be resolved with the newly developed technique of difference image analysis (DIA, Alard 1998, 1999; Alard & Lupton 1998; Alcock et al. 1999a, 1999b; Melchior et al. 1998, 1999). Since the DIA method detects and measures the variation of source star flux by subtracting an observed image from a convolved and normalized reference image, one can measure light variations even for unresolved stars. By using the DIA method, one can not only improve the photometric precision by removing the effect of blending but also increase the number of detected events by including unresolved stars into monitoring sources. In addition, the DIA method allows one to overcome the restriction of conducting lensing experiments toward only resolved star fields and thus can extend our ability to probe extra-galactic MACHOs (Gould 1995, 1996; Han 1996; Han & Gould 1996; Crotts & Tomaney 1996; Tomaney & Crotts 1996; Ansari et al. 1997, 1999).

However, the principal problem with the DIA method in microlensing experiments is that, by its very nature, it has difficulties in measuring the unamplified flux (baseline flux, $F_0$) of a source star. This is because the observed light curve[1] of a microlensing event obtained by the DIA method, $F_{\mathrm{DIA}}$, results from the combination of the true amplification $A_0$ and the baseline flux, i.e.

$$F_{\mathrm{DIA}} = F - F_{\mathrm{ref}} = F_0(A_0 - 1), \qquad (1.1)$$

where $F$ and $F_{\mathrm{ref}}$ represent the source star fluxes measured from the image obtained during the progress of the event and the reference image, respectively. One significant consequence of this problem is that it produces degeneracy in determining the lensing parameters of the event (see § 3) like the degeneracy problem for a blended event whose light curve results from the combination of $A_0$ and the blended flux. Therefore, it is often believed that the DIA method is not as powerful as the classical method based on the PSF photometry in determining the Einstein time scale $t_{\mathrm{E}}$ of an event.

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[1]Throughout this paper, we use the term 'light curve' to designate the changes in the *flux* of a source star, while the term 'amplification curve' is used to represent the changes in the *amplification* of the source star flux.

In this paper, we demonstrate that the degeneracy problem in microlensing events detectable from the searches by using the DIA method will not be as serious as it is often worried about. This is because a substantial fraction of events will be high amplification events for which the deviations of the amplification curves constructed with the wrong baseline fluxes from their corresponding best-fit standard amplification curves will be considerable even for a small amount of the fractional baseline flux deviation $\Delta F_0/F_0$. With a model luminosity function of source stars and under realistic observational conditions, we find that $\sim 30\%$ of detectable Galactic bulge events are expected to have high amplifications and their baseline fluxes can be determined with uncertainties $\Delta F_0/F_0 \leq 0.5$.

## 2. Mis-normalized Amplification Curves

The standard form of the amplification curve of a gravitational microlensing event is related to the lensing parameters by

$$A_0(u) = \frac{u^2 + 2}{u(u^2 + 4)^{1/2}}; \qquad u = \left[ \left( \frac{t - t_{\max}}{t_{E,0}} \right)^2 + \beta_0^2 \right]^{1/2}, \tag{2.1}$$

where $u$ is the lens-source separation normalized in units of the angular Einstein ring radius $\theta_E$, and the lensing parameters $\beta_0$, $t_{\max}$, and $t_{E,0}$ represent the impact parameter for the lens-source encounter, the time of maximum amplification, and the Einstein ring radius crossing time (Einstein time scale), respectively. Once these lensing parameters are determined from the amplification curve, one can obtain information about the lens because the Einstein time scale is related to the physical parameters of the lens by

$$t_{E,0} = \frac{r_E}{v}; \qquad r_E = \left( \frac{4GM}{c^2} \frac{D_{ol} D_{ls}}{D_{os}} \right)^{1/2}, \tag{2.2}$$

where $r_E = D_{ol}\theta_E$ is the Einstein ring radius, $v$ is lens-source transverse speed, $M$ is the mass of the lens, and $D_{ol}$, $D_{ls}$, and $D_{os}$ are the separations between the observer, lens, and source star.

However, if the baseline source star flux of an event is misestimated by an amount $\Delta F_0$, the resulting amplification curve $A$ (hereafter 'mis-normalized' amplification curve) deviates from the true amplification curve $A_0$ by

$$A = \frac{F_0 A_0 + \Delta F_0}{F_0 + \Delta F_0} = \frac{A_0 + f}{1 + f}, \tag{2.3}$$

where $f = \Delta F_0/F_0$ is the fractional deviation in the determined baseline flux.[2] If the baseline flux is overestimated (i.e. $f > 0$), the determined amplification is lower than $A_0$,

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[2]We note that if $f$ represents the blended light fraction, i.e. $f = B/F_0$, equation (2.3)

and vice versa. Note that while there is no upper limit for $f$, it should be greater than $-1$ (i.e. $f > -1$).

The shape of a microlensing event amplification curve is characterized by its height (peak amplification) and the width (event duration), which are parameterized by the impact parameter and the Einstein time scale, respectively. Since both the height and width of the amplification curve are changed due to the wrong estimation of the baseline flux, the lensing parameters determined from the mis-normalized amplification curve will differ from the true values. First, the change in the peak amplification makes the determined impact parameter change into

$$\beta = \left[ 2 \left( 1 - A_p^{-2} \right)^{-1/2} - 2 \right]^{1/2}; \qquad A_p = \frac{A_{p,0} + f}{1 + f}, \tag{2.4}$$

where $A_{p,0} = (\beta_0^2 + 2)/\beta_0(\beta_0^2 + 4)^{1/2}$ and $A_p$ are the peak amplifications of the true and the mis-normalized amplification curves. In addition, due to the change in the event duration, the determined Einstein time scale differs from the value $t_{E,0}$ by

$$t_E = t_{E,0} \left( \frac{\beta_{th}^2 - \beta_0^2}{\beta_{th,0}^2 - \beta^2} \right)^{1/2}, \tag{2.5}$$

where $\beta_{th}$ represents the maximum allowed impact parameter (threshold impact parameter) for a source star to be detected by having a peak amplification higher than a certain threshold minimum value $A_{th}$. With the right choice of the baseline flux, the required minimum peak amplification and the corresponding maximum impact parameter are $A_{th,0} = 3/\sqrt{5}$ and $\beta_{th,0} = 1$. However, since the detectability will be determined from the mis-normalized amplification curve, the actually applied threshold amplification and the corresponding impact parameter will differ from $A_{th,0}$ and $\beta_{th,0}$ by

$$A_{th} = A_{th,0}(1 + f) - f, \tag{2.6}$$

and

$$\beta_{th} = \left[ 2 \left( 1 - A_{th}^{-2} \right)^{-1/2} - 2 \right]^{1/2} \tag{2.7}$$

(Han 1999).

In the upper panels of Figure 1, we present four example mis-normalized amplification curves $A$ (solid curves) which are expected when the baseline flux of the source star for a

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describes the observed amplification curve of a microlensing event affected by blended light of an amount $B$. Therefore, the amplification curve of a blended event can be regarded as the mis-normalized amplification curve constructed with the baseline flux deviation $\Delta F_0 = B$. The only difference is that since the blended light should be positive, i.e. $f > 0$, while the baseline flux deviation can be either negative or positive, blended amplification curves are always underestimated.

microlensing event with $\beta_0 = 0.5$ is determined with the fractional deviations of $f = \pm 0.2$ and $\pm 0.5$. By using equations (2.4) – (2.7), we compute the lensing parameters of the standard amplification curves which best fit the individual mis-normalized amplification curves, and the resulting amplification curves $A_{\mathrm{fit}}$ are presented by dotted lines. In the lower panels, to better show the difference between each pair of curves $A$ and $A_{\mathrm{fit}}$, we also present the fractional deviations of the amplification curves $A$ from their corresponding best-fit standard amplification curves, i.e. $\Delta A / A_{\mathrm{fit}}$; $\Delta A = A_{\mathrm{fit}} - A$. From the figure, one finds the following trends. First, for the same amount of $|f| = |\Delta F_0| / F_0$, the fractional deviation $\Delta A / A_{\mathrm{fit}}$ is larger when the baseline flux is underestimated (i.e. $f < 0$) compared to the deviation when the baseline flux is overestimated (i.e. $f > 0$). Second, although the difference between the two amplification curves $A$ and $A_{\mathrm{fit}}$ becomes bigger as the deviation $\Delta F_0 / F_0$ increases, the mis-normalized amplification curves, in general, are well fit by standard amplification curves with different lensing parameters.

## 3. Baseline Flux Determination for High Amplification Events

In previous section, we showed that since the amplification curve of a general microlensing event obtained based on wrong estimation of the baseline flux is well fit by a standard amplification curve with different lensing parameters, making it difficult to determine $F_0$ from the shape of the observed light curves. In this section, however, we show that for high amplification events the deviations of the mis-normalized amplification curves from their best-fit standard curves are considerable even for a small fractional deviation $\Delta F_0 / F_0$, and thus one can determine the baseline fluxes with small uncertainties.

To demonstrate this, in the upper panels of Figure 2, we present the mis-normalized amplification curves constructed with the same fractional baseline flux deviations of $f = \pm 0.2$ and $\pm 0.5$ as the cases in Figure 1, and the corresponding best-fit standard amplification curves for a *higher* amplification event with an impact parameter of $\beta_0 = 0.1$. In the lower panels, we also present the fractional differences $\Delta A / A_{\mathrm{fit}}$. From the comparison of the fractional differences $\Delta A / A_{\mathrm{fit}}$ in Figure 1 and 2, one finds that the deviations of the mis-normalized amplification curves from their corresponding standard amplification curves are siginificantly larger for the higher amplification event.

To quantify how better one can determine the baseline flux with increasing event amplifications, we determine the uncertainty ranges of $F_0$ for microlensing events with various impact parameters $\beta_0$ under realistic observational conditions. To do this, for a given event with $\beta_0$ we first produce a series of mis-normalized amplification curves which are constructed with varying values of $f$. In the next step, we obtain the best-fit standard amplification curves corresponding to the individual mis-normalized amplification curves by using the relations in equations (2.4) – (2.7). We then statistically compare each pair of the

amplification curves $A$ and $A_{\text{fit}}$ by computing $\chi^2$, which are determined by

$$\chi^2 = \sum_{i=1}^{N_{\text{dat}}} \left[ \frac{A(t_i) - A_{\text{fit}}(t_i)}{pA_{\text{fit}}(t_i)} \right]^2. \tag{3.1}$$

For the computation of $\chi^2$, we assume that the events are observed $N_{\text{dat}} = 60$ times during $-1t_{\text{E}} \leq t \leq 1t_{\text{E}}$. The photometric uncertainty $p$ depends on the observational strategy, instrument, and source star brightness. Therefore, we determine the photometric uncertainty by computing the signal-to-noise ratio ($1/p = S/N$) under the assumption that events are observed with a mean exposure time of $t_{\text{exp}} = 150$ s by using a 1-m telescope equipped with a detector that can detect 12 photons/s for a $I = 12$ star. The detailed description about the signal-to-noise computation is described in § 4. Once the values of $\chi^2$ as a function of $f$ are computed, the uncertainty of $F_0$ is determined at $1\sigma$ (i.e. $\chi^2 = 1$) level. We then repeat the same procedures for events with various values of $\beta_0$ (and thus the peak amplifications).

In the upper of Figure 3, we present the resulting values of $\chi^2$ as a function of $\log(1+f)$ for example events with the source star brightness $I = 18$ and various impact parameters of $\beta_0 = 0.05$, 0.1, 0.2, and 0.22. In the lower panel, we also present the uncertainty range of $\Delta F_0/F_0$ (shaded region). From the figure, one finds the following trends. First, the uncertainty significantly decreases as the impact parameter decreases, implying that the baseline fluxes for high amplification events can be determined with small uncertainties. Second, if the impact parameter becomes bigger than a certain critical value ($\beta_{\text{crit}}$), the value of $\chi^2$ becomes less than 1, implying that the $F_0$ cannot be determined from the shape of the obtained light curve. For our example events with $I = 18$, this corresponds to $\beta_{\text{crit}} = 0.22$. Note that the uncertainty range $\Delta F_0/F_0$ in the lower panel is determined only for impact parameters yielding $\chi^2 \geq 1$. Third, the upper limit of the uncertainty range is always bigger than the lower limit.

Knowing that $F_0$ can be determined only for high amplification events, we define *the critical impact parameter* $\beta_{\text{crit}}$ as the maximum allowed impact parameter below which the baseline flux of the event can be determined with uncertainty less than 50% (i.e. $\chi^2 \geq 1$ and $\Delta F_0/F_0 \leq 0.5$. Then $\beta_{\text{crit}}(F_0)$ represents the average probability that the baseline flux of an event with a source star brightness $F_0$ can be determinded with an uncertainty less than 50%. We compute the critical impact parameters for events expected to be detected towards thd Galactic bulge, and they are presented in the upper panel of Figure 4 as a function of the source star brightness in $I$ band. From the figure, one finds that as the source star becomes fainter, the value of $\beta_{\text{crit}}$ decreases. This is because for a faint source event, the photometric uncertainty $p$ is large. Therefore, to be distinguished from standard amplification curves with a statistical confidence level higher than the required level (i.e. $\chi^2 \geq 1$), the event should be highly amplified.

## 4.   Fraction of High Amplification events

In previous section, we showed that the baseline fluxes of high amplification events can be determined with precision. In this section, we determine the fraction of high amplification events for which one can determine $F_0$ with small uncertainties among the total microlensing events detectable by using the DIA method.

Under the assumption that image subtraction is perfectly conducted[3], the signal measured from the subtracted image by using the DIA technique is proportional to the variation of the source star flux, i.e. $S \propto F_0(A_0 - 1)t_{\exp}$. On the other hand, the noise of the source star flux measurements comes from both the lensed source star and blended stars, i.e. $N \propto (F_0 A_0 + B)^{1/2}$, where $B$ is the background flux from blended stars in the effective seeing disk (i.e. the undistinguishable separation between images) with a size (i.e. diameter) $\Delta\theta_{\rm see}$. Then the signal-to-noise ratio of an event whose light variation is detected by using the DIA method is given by

$$S/N = F_0(A_0 - 1)\left(\frac{t_{\exp}}{F_0 A_0 + \langle B \rangle}\right)^{1/2}, \qquad (4.1)$$

where $\langle B \rangle$ represents the mean background flux. For a high amplification event $(A_0 \gg 1)$ with a bright source star $(F_0 A_0 \gg \langle B \rangle)$, the signal-to-noise ratio becomes photon limited, i.e. $S/N \sim (F_0 A_0 t_{\exp})^{1/2}$. By contrast, for a low amplification event with a faint source star $(F_0 A_0 \ll \langle B \rangle)$, the noise from the background flux becomes important. Let us define $\beta_{\max}(F_0)$ as the maximum impact parameter within which a lensing event can be detected by having signal-to-noise ratios higher than a certain threshold value $(S/N)_{\rm th}$ during a range of time longer than a required one $\Delta t$. Then, $\beta_{\max}(F_0)$ represents the average detection probability of an event with a source star brightness $F_0$ from the microlensing search by using the DIA method, and it is computed by

$$\beta_{\max} = \begin{cases} [u_{\max}^2 - (\Delta t/t_E)^2]^{1/2} & \text{when } u_{\max} \geq \Delta t/t_{\rm E} \\ 0 & \text{when } u_{\max} < \Delta t/t_{\rm E} \end{cases} \qquad (4.2)$$

where $u_{\max} = [2(1 - A_{\min}^{-2})^{-1/2} - 2]^{1/2}$ represents the threshold lens-source separation below which the signal-to-noise ratio of an event becomes greater than $(S/N)_{th}$ and $A_{\min}$ is the amplification of the event then $u=u_{\max}$. The value of $A_{\min}$ is obtained by numerically solving equation (4.1) with respect to the amplification for a given threshold signal-to-noise ratio of $(S/N)_{\rm th}$.

In the upper panel of Figure 4, we present the maximum impact parameter $\beta_{\max}$ as a function of the source brightenss for stars in the Galactic bulge. For the computation

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[3] A very ingeneous image subtraction method developed by Alard & Lupton (1998) demostrate that it is possible to measure the variable flux to a precision very close to the photon noise.

of $\beta_{\max}(F_0)$, we assume the same observational conditions described in § 3. The adopted threshold signal-to-noise ratio of the MACHO experiment is $(S/N)_{\rm th} = 10$ (Alcock 1999a, 1999b). In our computation, however, a higher value of $(S/N)_{\rm th} = 15$ is adopted to account for the additional noise from the sky brightness and the residual flux due to imperfect image subtraction. The average background flux is obtained by

$$\langle B \rangle = \int_0^{F_{\rm CL}} F_0 \Phi_0(F_0) dF_0, \tag{4.3}$$

where $F_{\rm CL}$ and $\Phi_0(F_0)$ are the crowding limit of the Galactic bulge field and the luminosity function of stars in the field normalized to the area of $\pi(\Delta\theta_{\rm see}/2)^2$. We adopt the luminosity function of Holtzman et al. (1998) constructed from the observations of bulge stars by using the *Hubble Space Telescope* and the adopted crowding limit is $I = 18.2$ mag. We assume that an event is detectable if signal-to-noise ratios are higher than $(S/N)_{\rm th}$ during $\Delta t = 0.2 t_{\rm E}$ of the source star flux variation measurements. From the figure, one finds that the detection probabilities (i.e. $\beta_{\max}$) of events with source stars faint than the crowding limit, and thus unresolvable, are not negligible up to $\sim 3$ mag below $F_{\rm CL}$ implying that a substantial fraction of events detectable by using the DIA method will be faint source star events (Jeong, Park, & Han 1999).

With the determined values of $\beta_{\max}$ as a function of source star brightness, we then construct the effective source star luminosity function by

$$\Phi_{\rm eff}(F_0) = \beta_{\max}(F_0)\Phi_0(F_0). \tag{4.4}$$

We also construct the luminosity function of source stars for high amplification events with measurable baseline fluxes by

$$\Phi_{\rm high} = \eta(F_0)\Phi_0(F_0); \qquad \eta = \begin{cases} \beta_{\rm crit}/\beta_{\max} & \text{when } \beta_{\rm crit} \leq \beta_{\max} \\ 1.0 & \text{when } \beta_{\rm crit} > \beta_{\max} \end{cases} \tag{4.5}$$

Once the two luminosity functions $\Phi_{\rm eff}$ and $\Phi_{\rm high}$ are constructed, the fraction of high amplification events out of the total number of detactable events is computed by

$$\frac{\Gamma_{\rm high}}{\Gamma_{\rm tot}} = \frac{\int_0^\infty \Phi_{\rm high}(F_0) dF_0}{\int_0^\infty \Phi_{\rm eff}(F_0) dF_0}. \tag{4.6}$$

We find that for $\sim 33\%$ of events detectable from the microlensing searches by using the DIA method will have high amplification events for which the baseline fluxes can be determined with uncertainties $\Delta F_0/F_0 \leq 0.5$.

## 5. Conclusion

We have investigated how the lensing parameters change due to the wrong determination of the baseline flux of a microlensing event. We have also investigated the feasibility of the baseline flux determination from the shape of the observed light curve. The results of these investigations are as follows:

1. The obtained amplification curve of a general microlensing event based on wrong baseline flux is well fit by a standard amplification curve with different lensing parameters, implying that precise determination of $F_0$ from the shape of the observed light curve will be difficult.

2. However, for a high amplification event, the mis-normalized amplification curve deviates from the standard form by a considerable amount even for a small fractional deviation of baseline flux, allowing one to determine $F_0$ with a small uncertainty.

3. With a model luminosity function of Galactic bulge stars and under realistic observational conditions of the microlensing searches with the DIA method, we find that a substantial fraction ($\sim 33\%$) of microlensing events detectable by using the DIA method will be high amplification events, for which the baseline fluxes of source stars can be determined with uncertainties $\Delta F_0 / F_0 \leq 50\%$.

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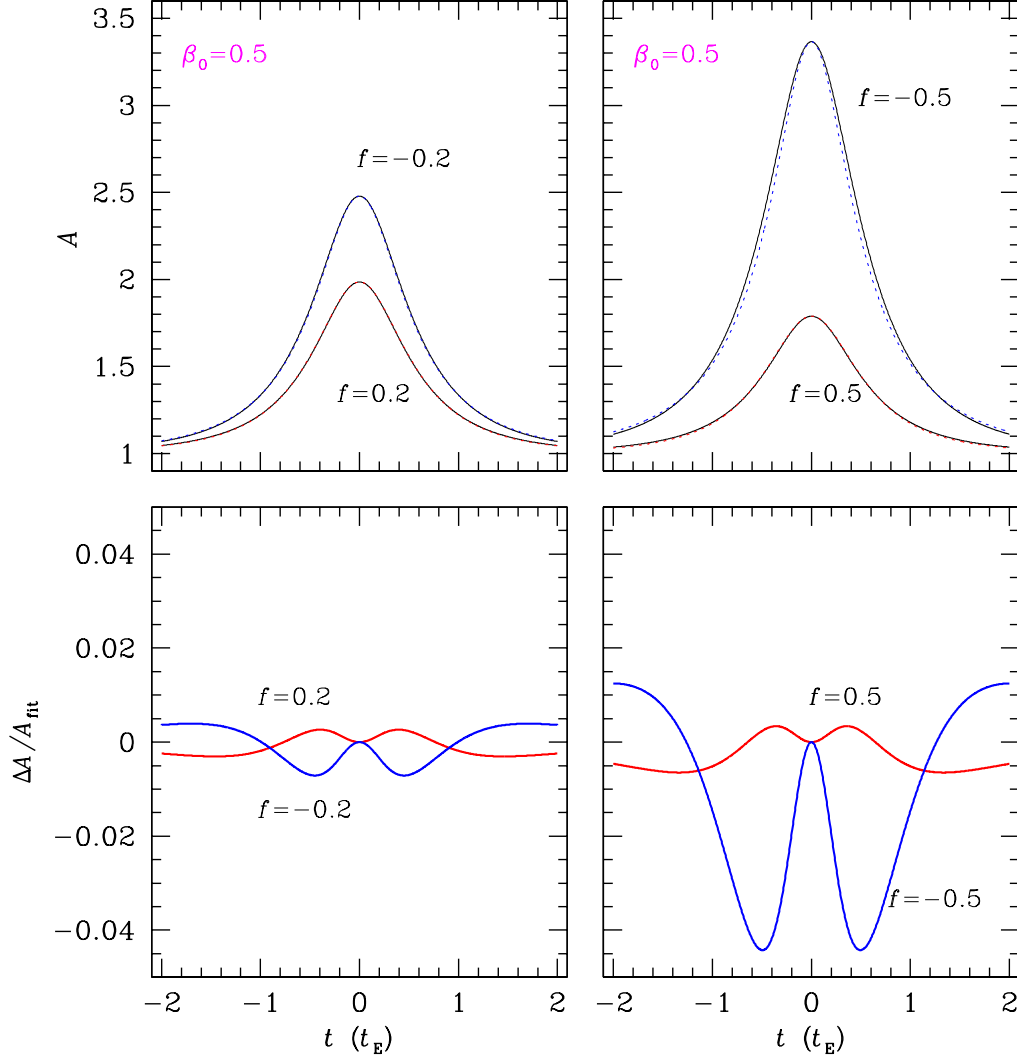Woźniak, P., & Paczyński, B. 1997, ApJ, 487, 55

**Figure 1:** Upper panels: four example mis-normalized amplification curves (solid curves) which are expected when the baseline flux of the source star for a microlensing event with $\beta_0 = 0.5$ is determined with the fractional deviations of $f = \pm 0.2$ and $\pm 0.5$. Also presented are the standard amplification curves ($A_{\mathrm{fit}}$, dotted curves) which best fit the individual mis-normalized amplification curves. Lower panels: the fractional deviations of the mis-normalized amplification curves from their corresponding best-fit standard amplification curves, i.e. $\Delta A / A_{\mathrm{fit}}$; $\Delta A = A_{\mathrm{fit}} - A$.
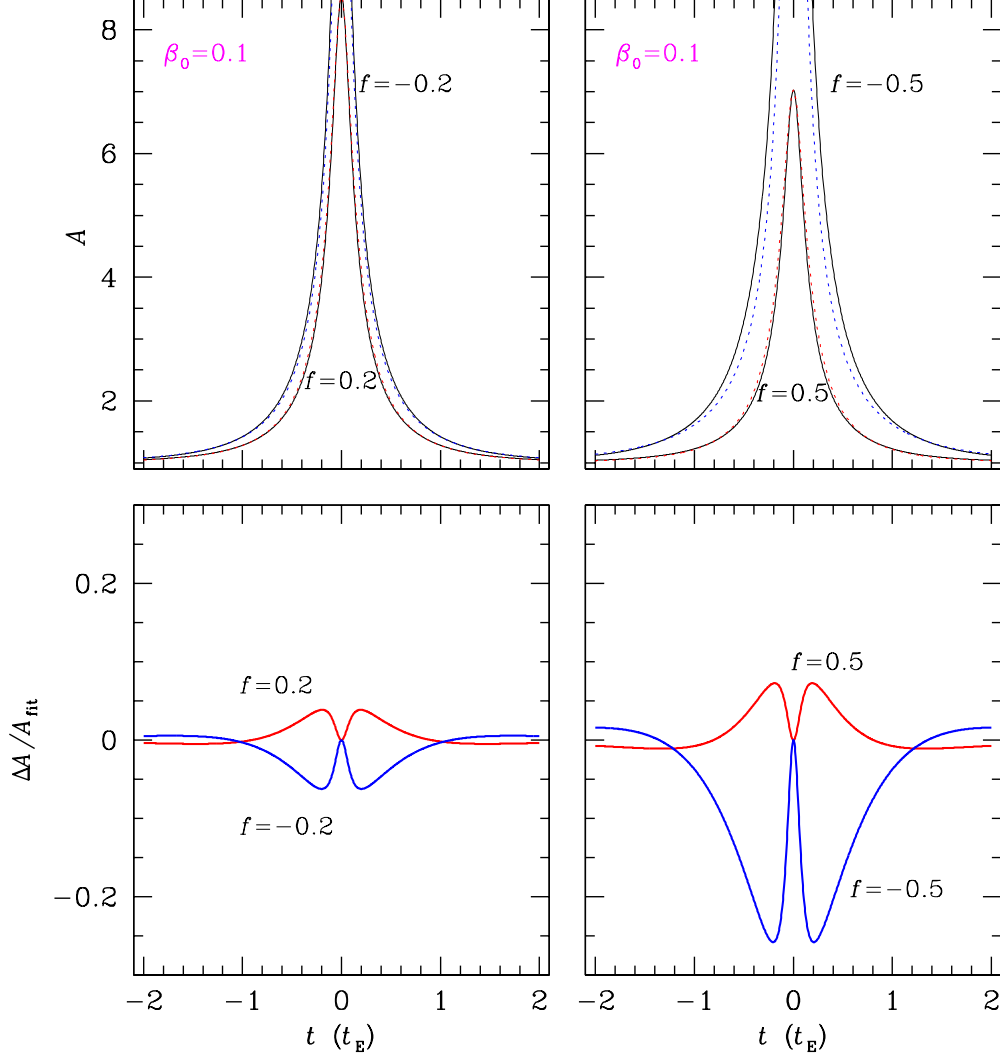
**Figure 2:** Upper panel: the mis-normalized amplification curves with the same fractional baseline flux deviations of $f = \pm 0.2$ and $\pm 0.5$ as the cases in Figure 1, and the corresponding best-fit standard amplification curves for a *higher* amplification event with $\beta_0 = 0.1$. Lower panel: the fractional differences between the amplification curves $A$ and $A_{\mathrm{fit}}$.
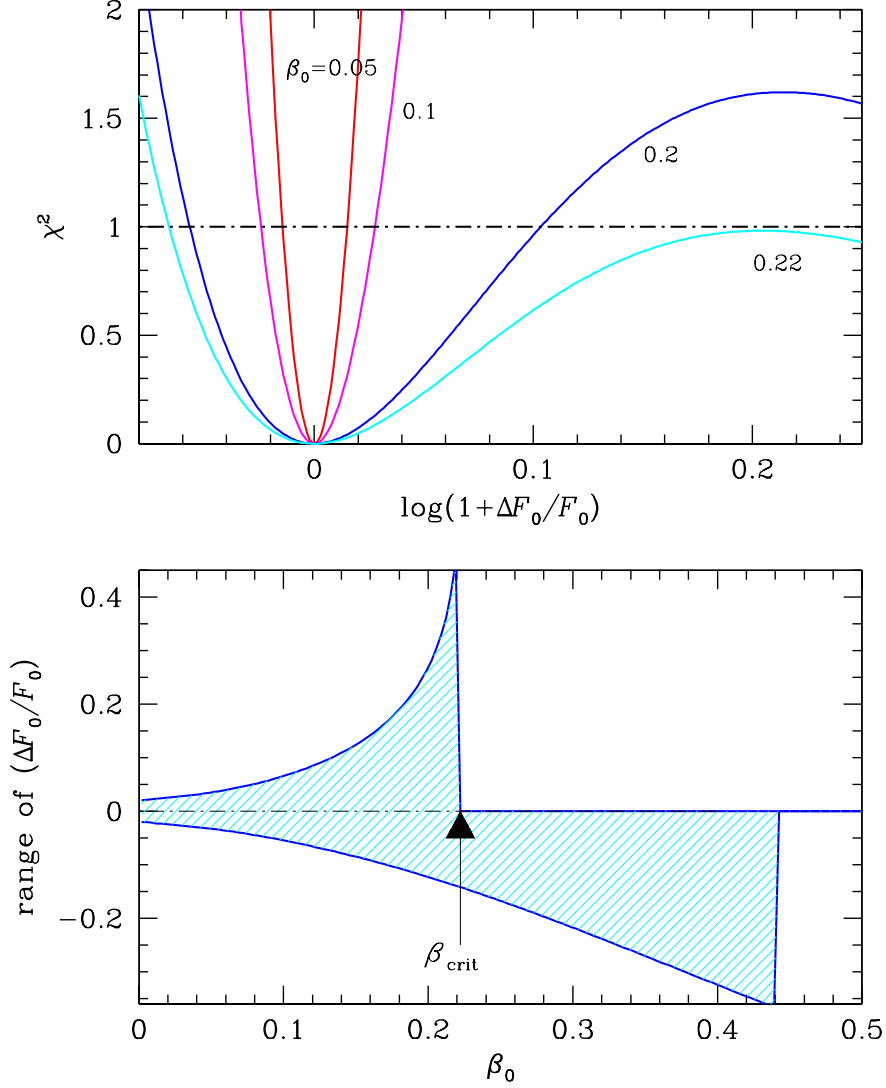
**Figure 3:** Upper panel: the values of $\chi^2$ as a function of $\log(1 + \Delta F_0/F_0)$ for example events with a source star brightness of $I = 18$ and various impact parameters $\beta_0$. The value of $\chi^2$ is computed by comparing the mis-normalized amplification curve with a fractional baseline flux deviation $f = \Delta F_0/F_0$ and the corresponding best-fit standard amplification curve. Lower panel: the uncertainty range of the baseline flux (shaded region) determined from the shape of the light curve of a lensing event detected by using the DIA technique. The uncertainties are determined at $1\sigma$ (i.e. $\chi^2 = 1$) level.
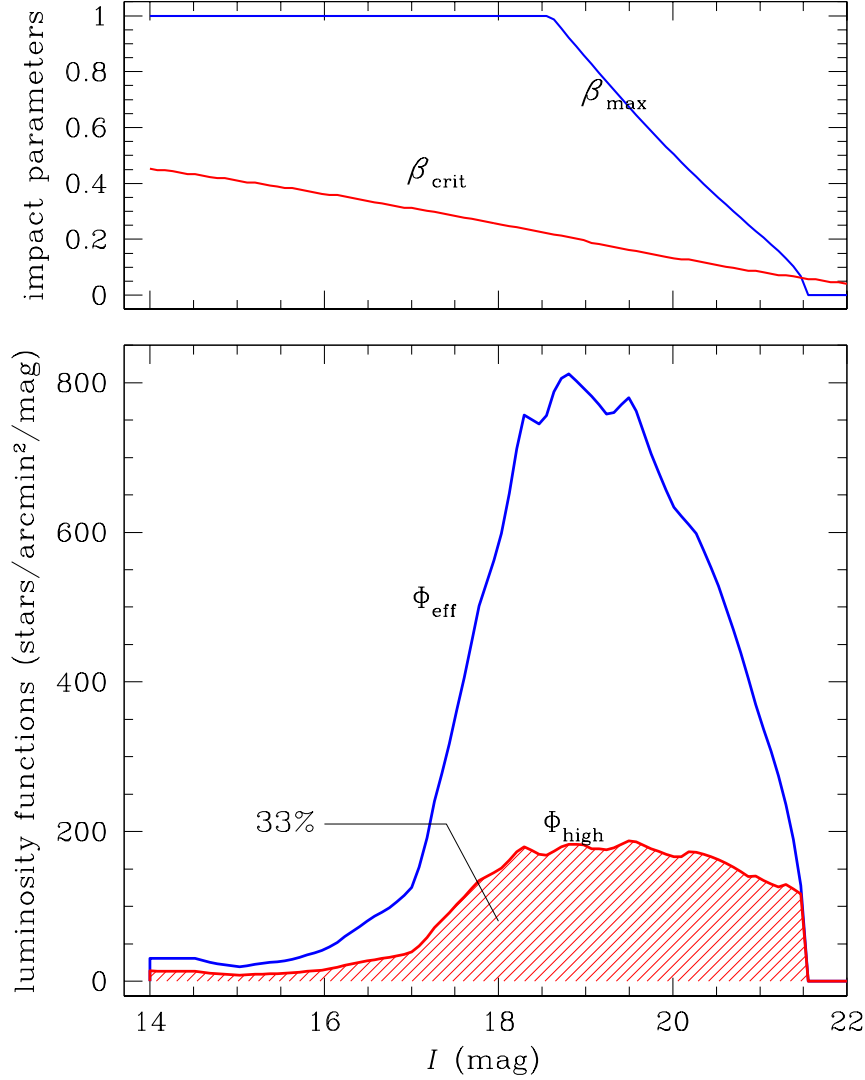
**Figure 4:** Upper panel: the critical and the maximum impact parameters ($\beta_{\mathrm{crit}}$ and $\beta_{\mathrm{max}}$) as functions of the source brightness for stars in the Galactic bulge field. The value of $\beta_{\mathrm{max}}$ is equivalent to the average detection probability of an event with a source star brightness $I$ from the microlensing search by using the DIA method. On the other hand, $\beta_{\mathrm{crit}}$ represents the average probability that the baseline flux of an event with a source star brightness $I$ can be determined with an uncertainty less than 50%. Lower panel: the effective source star luminosity functions of the total ($\Phi_{\mathrm{eff}}$) and high amplification events ($\Phi_{\mathrm{high}}$) detectable from the microlensing searches by using the DIA technique toward the Galactic bulge field. The shaded region represents the fraction of high amplification events.